HSCT Mission Analysis of Waverider Designs

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Final Report

(May 15, 1991 - May 14, 1993)

In May of 1991, grant NAG-1-1295 was awarded to Dean A. Richard Seebass and Dr. F. Carroll Dougherty of the University of Colorado by the Mission Analysis Branch at NASA Langley under branch chief Bill Small for the period May 15, 1991, to May 14, 1992. A one year extension was later obtained, making the completion date May 14, 1993.

The grant provided partial support for an investigation of waverider design and analysis with application to High-Speed Civil Transport (HSCT) vehicles. Proposed was the development of the necessary CFD tools for the direct simulation of the waverider vehicles, the development of two new waverider design methods that would provide computational speeds and design flexibilities never before achieved in waverider design studies, and finally the selection of a candidate waverider-based vehicle and the evaluation of the chosen vehicle for a canonical HSCT mission scenario.

This, the final report, reiterates the proposed project objectives in moderate detail, and it outlines the state of completion of each portion of the study, providing references to current and forthcoming publications that resulted from this work.

Project Objectives

Objectives in three areas were originally proposed: the completion of a package of CFD tools for the direct simulation of waverider-type configurations, the development of two new inverse methods for the design of waveriders, and the mission analysis of a waverider-based HSCT candidate vehicle. The proposed work in each of these catagories, including the state of development at the initiation of the study as well as the desired state at the completion of the study, is briefly summarized in the following subsections.

Direct Simulations

At the onset of this project, a reasonably complete package of tools had been compiled for the direct simulation of inviscid and viscous flows about waverider-like configurations. These tools were developed by the current investigators along with Dr. Helmut Sobieczky

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of the DLR in Göttingen, Germany, and two graduate research assistants, Kevin D. Jones and Kenneth B. Center and included a robust geometry generation tool,[1] several analytic and spline-fitting surface-mapping routines, a newly developed Trans-Finite Interpolation (TFI) grid generator, a version of the NASA Ames partially flux-split flow solver, F3D, with specialized boundary condition subroutines for handling stagnation-free sharp leading edges, and a newly developed spline-fitting, solution-based grid adaptation scheme.

Preliminary work with these routines demonstrated their ability to accurately simulate high-speed flowfields about waverider configurations through comparisons with theory or known solutions, through comparisons with other numerical results that were widely accepted in the research community, and through comparisons with experimental data.[2,3,4,5,6]

These tools were to be further developed into a more robust package in order to validate results from the new inverse design codes. These new waverider-based configurations were to have sharp and/or rounded leading edges and highly convex and/or concave surface features, but all would have known shock locations. Suitable grid generation and accurate flow solving capabilities were desired, requiring further modification and debugging of the existing software.

Inverse Waverider Design

Two new inverse design algorithms were in the early stages of development at the start of this project. The two methods, originally proposed by Sobieczky et al.[4,5], were the osculating cones method and the cross-stream marching method.

The first approach, the osculating cones method, was being developed by Kenneth B. Center into an efficient and powerful interactive design tool, WIPAR (Waverider Interactive Parameter Adjustment Routine).[7] At the initiation of the current study, WIPAR provided fully interactive adjustment of shock geometry, flow capture tube, and flow parameters that defined the conical flowfields. The proposal called for WIPAR to be extended to include low-speed aerodynamic analysis and weight and balance computations. Additionally, viscous analysis and on-design force and moment integrations were desired for accurate optimization of the configurations.

The second approach, the cross-stream marching method, was proposed by Kevin D. Jones for computing the flowfields behind more general shock geometries in the interest of generating a new class of variable shock-strength waveriders. A prototype code developed by Sobieczky et al.[4,5] demonstrated the utility of the approach, albeit with a much simplified vertical marching procedure. The proposal called for developing a robust algo-

rithm, SCIEMAP (Supersonic Cross-stream Inverse Euler Marching Program), that would march in a direction that would eliminate or, at least, minimize the effects of the three-dimensional problem's ill-posedness. If necessary, filtering and smoothing techniques were to be investigated to suppress instabilities that might arise due to the ill-posedness of the problem.

Mission Analysis

The last objective of the proposal called for the selection of a candidate waverider topology and the analysis of the chosen configuration for a canonical HSCT mission scenario. No work had been initiated by the involved researchers in the field of waverider-based HSCT mission analysis, but four computer codes, AWAVE, AERO2S, AWDES, and FLOPS, were to be provided by the Mission Analysis Branch at NASA Langley for the computation of subsonic and supersonic aerodynamic performance, and optimum mission design.

Project Status

In this section the status of each of the three proposed tasks at the completion of the study is discussed in some detail with references to resulting publications. Subsections here are consistent with the subsections above, and summarize the progress made during the period of the grant.

Direct Simulations

It is reasonable to state that the package of CFD tools for the direct simulation of waverider vehicles is complete within the bounds outlined in the proposal. Several modifications were made in the grid generator, HYGRID, and the flow solver, F3D, to better enable them to cope with the waverider configurations.

The grid generator was modified to accept more flexible leading edge geometries while minimizing grid irregularities. These changes were put to use on several test configurations including a NASP-like, waverider forebody with a rounded leading edge and a canopy produced by Sobieczky and Stroeve.[1]

After a presentation at the *AIAA 22nd Fluid Dynamics, Plasma Dynamics & Lasers Conference*,[6] an inconsistency between the pressure integration procedure employed by F3D and the accepted practices of other numerical analists and experimentalists was discovered. This inconsistency led to an apparent error in computed drag for flow simulations

about truncated bodies with finite base areas. Modifications were made to conform to the accepted approach (i.e., freestream pressure acting on the vehicle's base), and results from this were published by Jones and Dougherty.[8]

Inverse Waverider Design

The most significant achievments were made in this area. Two very powerful algorithms have been developed providing design flexibility and computational speeds never before available in waverider design. With computational codes such as WIPAR and SCIEMAP, there is always room for additional features, but it is fair to say that both programs are now complete. Some of the proposed features proved to be unnecessary or unobtainable; whereas, other features not in the original proposal became apparent and were incorporated into the algorithms.

Complete details of the numerical algorithms and demonstrations of the application and accuracy of WIPAR and SCIEMAP can be found in the dissertations of Kenneth B. Center and Kevin D. Jones, repectively.[9,10] Additionally, initial work on both methods was presented at the *18th Congress of ICAS* in Beijing, Peoples Republic of China, by Center et al.,[11] preliminary results from SCIEMAP were presented at the *31st AIAA Aerospace Sciences Meeting* in Reno by Jones et al.,[12] and journal publications are in progress for both algorithms.[13,14,15,16] The final state of the algorithms is briefly summarized in the following subsections.

WIPAR This program allows the user to interactively vary the parameters that define the shape and strength of the shock wave and the shape of the waverider's leading edge, while instantaniously viewing the three-dimensional topology of the resultant waverider and monitoring the the new vehicle's aerodynamic performance. This instantanious manipulation of parameters with real-time graphic portrayal of results is made possible through the use of modern workstations and efficient programing.

WIPAR employs the osculating cones technique of Sobieczky et al.,[4,5] whereby a nonconical flowfield behind a shock of constant strength is approximated by many small regions of locally conical flow that are governed by the Taylor-Maccoll equation. The method is exact for axisymmetric, conical shocks, and still the results have been shown to be quite good for shocks that are extremely nonconical. The design flexibility provided by the method allows for the rapid generation of an endless variety of waverider configurations, as illustrated in Fig. 1.

A user guided optimization procedure is coupled with the algorithm, allowing the user to quickly scan a selected parameter space for local optima based on a selected performance criteria or a combination of these criteria. The real-time interaction allows the user to manually constrain the optimization to realistic geometries, as often unconstrained optimization processes lead to useless results.

The computation of low-speed aerodynamic performance originally proposed requires the use of a separate algorithm from that which is used to design the waveriders. This feature was deemed unnecessary, as existing codes were available from NASA to perform these computations. Also, an in-depth weight and balance analysis requires substantial knowledge of the aircraft componentry which is often not available. However, the center of volume may be easily computed and it may be used as a low-order approximation of the center of mass of the vehicle during the preliminary design stages.

SCIEMAP This program allows the user to specify a piece of a three-dimensional shock surface, and then the code computes the flowfield behind the shock by marching the Euler equations away from the shock surface in an essentially cross-stream direction. The general three-dimensional cross-stream marching problem is mathematically ill-posed; that is, unique, bounded solutions may not exist. However, by marching within the local osculating plane, the three-dimensional problem is reduced to a series of two-dimensional ones which are more stable.

Once the flowfield is computed, a waverider lower surface is generated in the usual way, by integrating a streamsurface (used as the waverider's lower surface) downstream from a user-defined leading edge. An upper surface is defined, and the flowfield there is predicted by an approximation to the axisymmetric method of characteristics.[9]

SCIEMAP can be used to duplicate many results from past waverider studies, but it is capable of producing a class of waveriders never before possible, with nonaxisymmetric shock surfaces and nonconstant shock strength. Interestingly, while the application to waverider design provides a powerful new tool for researchers in the field, the cross-stream marching approach employed by SCIEMAP may have many other applications such as intake design and internal flows.

Mission Analysis

In order to design and optimize a mission for a waverider-based HSCT, a number of preliminary tasks must be performed. The first task is the selection of a candidate vehicle. Manual optimization using the WIPAR code yielded the aircraft shown in Fig. 2, with

an on-design cruise-speed of Mach 4 and an L/D of about 7.4 (Note, this value of L/D neglects the affects of the vertical fins, engines, and other features added to the waverider base vehicle). Details of the selection process may be found in Ref. 9.

A computer code, FLOPS, was provided by NASA for the design and optimization of an HSCT mission. In order to use the code, performance data over a wide flight envelope had to be provided, including, zero-lift wave drag, lift and both pressure and viscous drag coefficients, for a broad range of Mach numbers and angles of attack.

Using the NASA developed AERO2S code for subsonic analysis and the AWDES code for supersonic analysis, off-design performance across the full anticipated flight envelope was computed. The computed lift coefficient, pressure drag coefficient, and lift-to-drag values have been extracted and compiled in graphical format, so that the waverider's performance can be contrasted with that of the traditional HSCT configuration detailed in NASA Technical Memorandum 4223.[17] Results from this (given in Ref. 9) compare well with those given in Ref. 17, demonstrating the competitiveness of the waverider-based configuration.

Technical difficulties arose applying the zero-lift wave drag code, AWAVE, on the waverider-based vehicle and could not be resolved in time to be useful in this study. Additionally, an accurate method for predicting the viscous drag coefficient was not available except at the on-design cruise conditions. These two difficulties prevented the utilization of the FLOPS mission design code.

Conclusions

Comparison of the results obtained in this study with those published for the Mach 4 HSCT of NASA Langley seem to indicate, at least upon initial inspection, that the candidate waverider configuration is competitive. Of course this configuration does not include control surfaces, engines, and other necessary features which add significant drag penalties, but it is also true that the results presented here are for a partially optimized waverider; this is certainly not the best that can be achieved. At the present time, however, it was felt that it was more important to ensure that the codes used in the off-design analysis were producing reasonable results. Now that their accuracy is confirmed, a study may commence to design and investigate better candidates for the prescribed mission.

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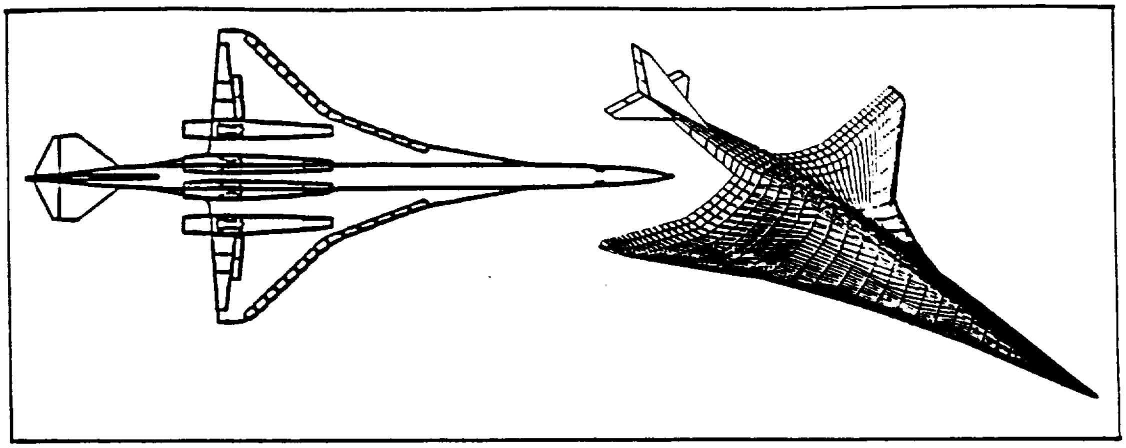

Figure 1a: An osculating cones waverider designed for a Mach 4 high-speed civil transport mission compared to an existing competitor.

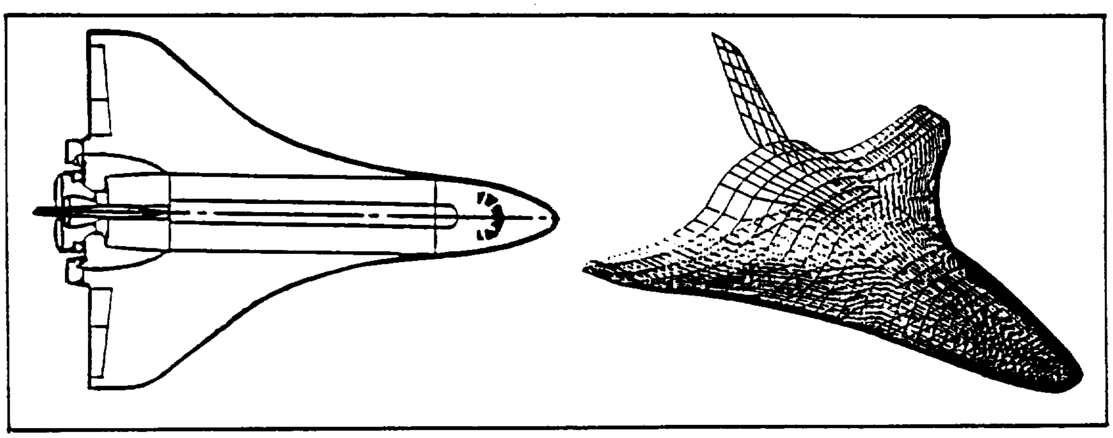

Figure 1b: An osculating cones waverider designed at a design Mach number of 25 resembling the space shuttle orbiter.

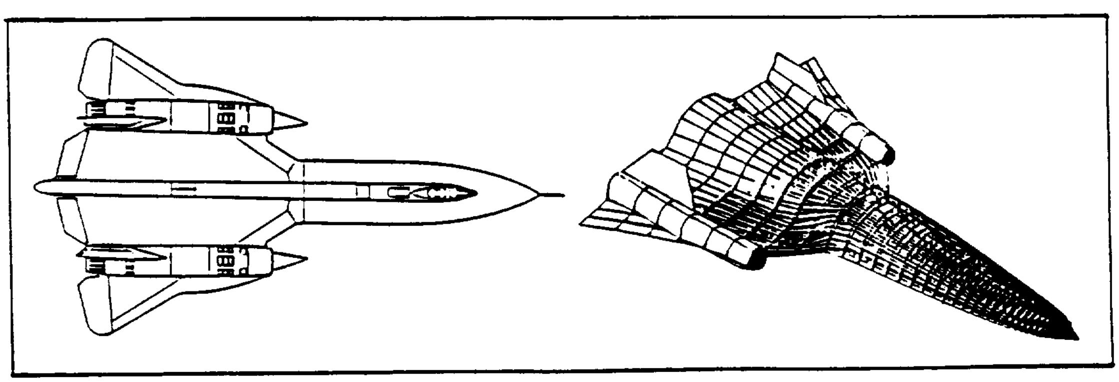

Figure 1c: A Mach 5 viscous-optimized osculating cones waverider which curiously resembles the Lockheed SR-71.

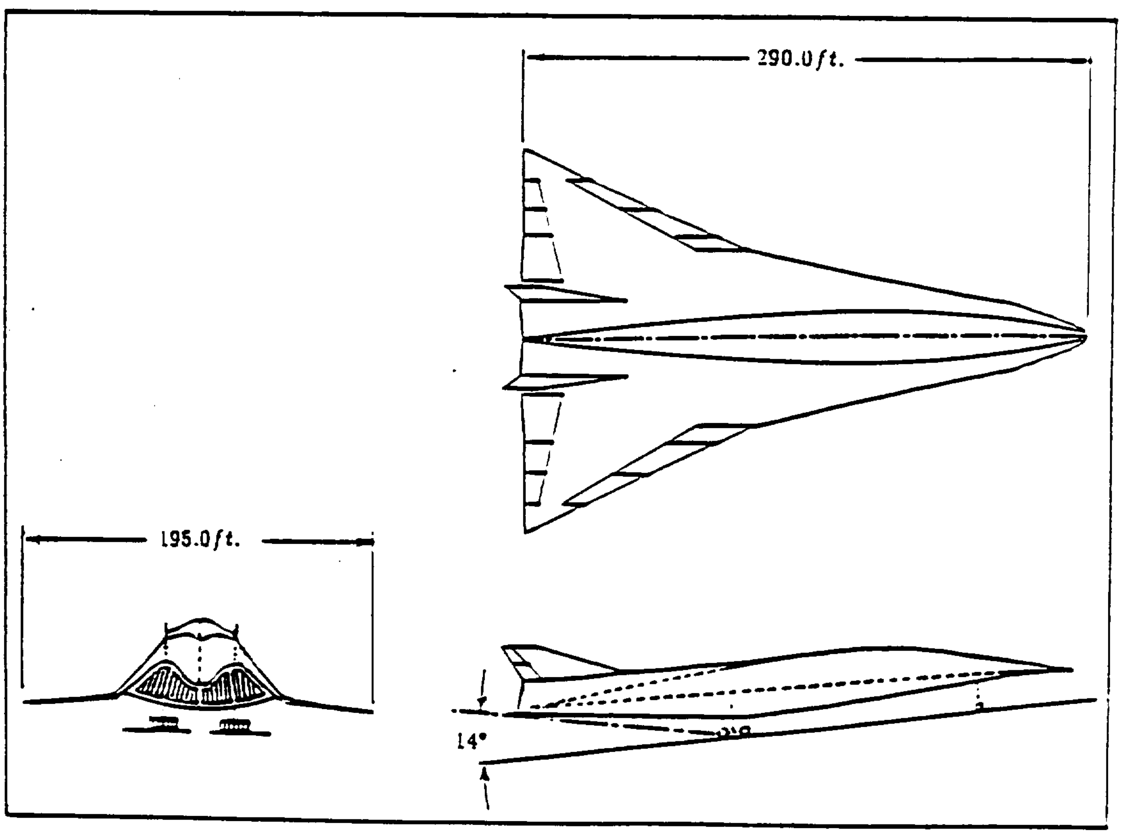

Figure 2: Waverider-based Mach 4 HSCT candidate.